AN INQUIRY INTO THE EFFECT OF METEOROLOGICAL CONDITIONS UPON THE EFFICIENCY OF STORAGE, FILTRATION, AND CHLORINATION, BASED UPON A STUDY OF THE HAGERSTOWN WATER SUPPLY[1]

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For several years past the quality of the Hagerstown, Md., water supply has been the source of considerable discussion, on account of the wide fluctuations in daily physical and hygienic quality. The various attempts to obviate these difficulties by increases in chlorine dosage up to excessive points have not served to eliminate, in any appreciable degree, the sudden and recurrent rises in bacterial content. In view of this state of affairs, a detailed study of the Hagerstown water supply situation, with particular reference to the cause of its varying sanitary condition, has been carried out. The results of this study are set forth below.

Hagerstown obtains its water during most seasons of the year from Warner Gap Hollow and Raven Rock Hollow, two small streams located on South Mountain. The drainage area of Warner Gap Hollow is 2.65 and that of Raven Rock Hollow 3.20 square miles, a total of 5.85 square miles. No storage is provided in Raven Rock Hollow but all the water, except during times of high flow, is diverted into a pipe line and run into Edgemont Reservoir, which is located in Warner Gap Hollow and has a capacity of 95,000,000 gallons. The inlet is located within a short distance of the outlet of Edgemont Reservoir, as shown in figure 1. From Edgemont Reservoir the water is delivered through a 12-inch cast iron and a 16-inch wood stave pipe to a reservoir of 20,000,000 gallons capacity located at Smithsburg. The water leaving this reservoir is treated with liquid chlorine and is brought to Hagerstown through two cast iron pipes, 12 inches and 16 inches in diameter respectively.

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The drainage areas of the streams in Warner Gap and Raven Rock Hollows, while of mountainous character, support more or less population. Thorough sanitary surveys of these drainage areas have been made by the Maryland State Department of Health and numerous nuisances have been corrected. The water company now maintains a regular patrol.

Whenever the amount of water obtainable from South Mountain is not sufficient to supply Hagerstown the water company puts into operation a rapid sand filtration plant which was constructed some years ago at Bridgeport. Water for supplying this plant is taken from Antietam Creek at this point, is filtered and disinfected but not softened, and is then pumped to Hagerstown through the existing 12-inch and 16-inch pipe lines running from South Mountain.

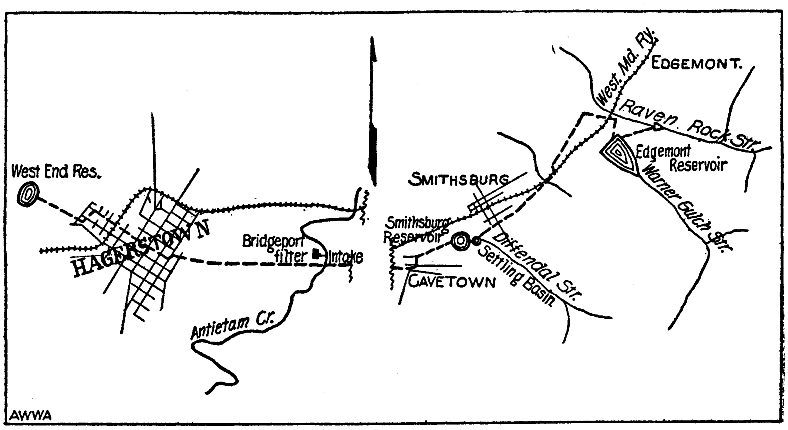

FIG. 1. SOURCES OF HAGERSTOWN WATER SUPPLY

The usual method followed in supplying Hagerstown with water is to use the South Mountain source as long as water is available in the Edgemont Reservoir; when the water in this reservoir has been drawn down to a low point the Bridgeport filtration plant is started and is then operated until rains replenish the reservoir. The period during which the filtration plant is operated varies from year to year as weather conditions make necessary.

The quality of the tap water has not been sufficiently good in past years and has been the subject of study by the State Department of Health. Robert B. Morse, Chief Engineer of the Department, has recommended in past years the relocation of the Raven Rock intake, so as to permit the water to enter the Edgemont

Reservoir at its head, the construction of a settling and coagulating basin at Smithsburg, to make more effective the intermittent application of alum to the mountain supply, and methods of operation of the Bridgeport filtration plant.

These improvements have not yet been completed but their necessity is made apparent by the confirmatory analytical data here discussed.*

In order to make a complete study of the water supply of a city in which the source of water is subject to considerable fluctuations in physical and hygienic quality, it is essential to have available a long and continuous series of analytical results. In the absence of such an extended series, it is not only impossible to measure accurately the variations in daily quality, but it becomes difficult to predict with certainty just what modifications will eliminate future objectionable conditions.

In Hagerstown, fortunately, we have at hand a complete history of the tap water for the period from February 11 to September 30, 1918, based upon examinations made by the city's analyst. The period since February 11 is used in this study because it is only since that date that the analyses have followed closely and consistently a standard procedure. These are used in place of the routine State determinations on account of their greater frequency and because they are not subject to the varying effects resulting from delays in transportation. They afford the only reliable continuous daily record of Hagerstown tap water quality now available.

The purpose of the present study is not only to analyze the past quality of the water, but to endeavor to obtain from present sources of information the possible causative factors of such fluctuations in the water as have occurred. This attempt is directed, therefore, more towards determining the causes of *variation* in, than towards grading, the quality of the tap water, It is apparent that, if such a study is successful in determining the causes of fluctuation in quality, the elimination of such causes becomes a matter of practical readjustment, with a necessary consequent improvement in general quality.

The unit of measure which is to serve as the index in this study will be the number of B. coli per 100 cc. found, either by presumptive or isolation test, in the tap water each day. The evaluation of

* Certain recent extensions at Bridgeport make the operation of the filtration plant more satisfactory.

TABLE 1

Elevation of water in inches above or below the spillway of Edgemont Reservoir, rainfall in inches per day at Chewsville, and B. coli in 100 cc. in tap water, during part of 1918

February	10	11	12	13	14	15	16	17	18	19
Reservoir elev.	−374	−350	−312	−228	−144	−72	+6	+5	+4	+4
Rainfall		T.			0.06	*			†	‡
B. coli, presump.	2	2	5	15	35				9	5
B. coli, isolation	0	0	5	15	35				9	5
February	§20	21	22	23	24	25	26	27	28	*M.* 1
Reservoir elev.	+7	+5	+4	+4	+4	+4	+4	+4	+4	+4
Rainfall	0.65		0.05			T.	0.46		¶	
B. coli, presump.	5	2	0	5		2	5	5	5	9
B. coli, isolation	5	2	0	0		2	0	0	5	0
March	2	3	4	5	6	7	8	9	10	11
Reservoir elev.	+4	+3	+3	+2	+2	+2	+2	+2	+3	+2
Rainfall			‡	0.40	T.			0.29	T.	
B. coli, presump.	2		9	2	5	2	5	5		5
B. coli, isolation	0		9	0	0	0	2	0		0
March	12	13	14	15	16	17	18	19	20	21
Reservoir elev.	+2	+2	+3	+3	+2	+2	+2	+2	+2	+2
Rainfall	0.04	1.05	0.63							T.
B. coli, presump.	2	5	5	2	2		2	2	2	2
B. coli, isolation	0	2	2	0	0		0	0	2	0
March	22	23	24	25	26	27	28	29	**30	31
Reservoir elev.	+1	+1	+1	+1	+1	+1	+1	+1	0	−1
Rainfall										
B. coli, presump.	5	5		2	2	2	5	2	5	
B. coli, isolation	2	2		0	0	0	2	0	2	
April	1	2	3	4	5	6	7	8	9	10
Reservoir elev.	−3	−4	−4	−5	−7	−9	−12	−15	−10	+12
Rainfall	T.		0.04					0.40	0.90	1.75
B. coli, presump.	2	9	5	2	2	5		2	5	2
B. coli, isolation	0	5	2	0	0	2		0	5	2
April	§11	12	13	14	15	16	17	18	19	20
Reservoir elev.	+7	+6	+5	+3	+4	+7	+6	+4	+3	+3
Rainfall	0.70	0.34	0.15							0.32
B. coli, presump.	2	2	5		2	0	2	5	2	2
B. coli, isolation	0	2	0		0	0	0	2	2	0
April	21	22	23	24	25	26	27	28	29	30
Reservoir elev.	+8	+6	+4	+3	+2	+2	+2	+1	+1	0
Rainfall	1.06		0.03	0.03	0.40				0.06	
B. coli, presump.		2	5	5	5	2	2		2	5
B. coli, isolation		0	2	0	0	2	2		0	5
May	**1	2	3	4	5	6	7	8	9	10
Reservoir elev.	+3	+3	+3	+3	+3	+3	+3	+3	+2	+2
Rainfall	0.25			0.03				0.11		0.14
B. coli, presump.	5	2	2	5		2	5	2	5	9
B. coli, isolation	5	0	0	2		0	2	0	5	2

* February 12–18; heavy runoff from watershed.

† February 18–20; temperature below freezing.

‡ Precipitation included in the next following measurements.

§ Raven Rock stream cut off.

¶ Water from Edgemont Reservoir turbid.

** Raven Rock stream turned on.

TABLE 1—*Continued*

May	11	12	13	14	15	16	17	18	19	20
Reservoir elev.	+2	+1	+1	+2	+2	+1	+1	+1	0	−1
Rainfall			0.20	0.20						
B. coli, presump.	5		9	9	5	5	5	2		9
B. coli, isolation	2		5	9	2	2	2	0		5
May	21	22	23	24	25	26	27	28	29	30
Reservoir elev.	−3	+4	+3	+2	+1	+1	0	−1	−2	−3
Rainfall	0.45		0.52						0.26	0.12
B. coli, presump.	20	9	5	5	9		9	5	12	9
B. coli, isolation	12	5	2	2	9		5	2	8	2
June	*M.* 31	1	2	3	††4	5	6	7	8	9
Reservoir elev.	−4	−5	−7	−9	−12	−15	−18	−22	−27	−33
Rainfall	0.65							0.25		
B. coli, presump.	5	5		5	9	5	5	2	5	
B. coli, isolation	2	2		5	9	2	2	0	0	
June	10	11	‡‡12	13	14	15	16	17	18	19
Reservoir elev.	−39	−46	−53	−61	−70	−80	−91	−100	−108	−116
Rainfall		0.09			0.09				T.	
B. coli, presump.	9	5	5	5	5	2		2	5	2
B. coli, isolation	5	2	2	0	2	0		0	0	0
June	20	21	22	23	24	25	26	27	§§28	29
Reservoir elev.	−124	−132	−126	−129	−135	−142	−149	−166	−165	−174
Rainfall		0.15	0.59	T.		0.01	0.03			0.03
B. coli, presump.	2	0	2		2	0	2	5	5	
B. coli, isolation	0	0	2		0	0	2	2	5	
July	*J.* 30	1	2	3	4	5	6	7	8	9
Reservoir elev.	−178	−186	−196	−207	−218	−230	−242	−256	−271	−287
Rainfall	0.65					0.27	T.			
B. coli. presump.		9	20	9	5	5	5		5	2
B. coli. isolation		5	12	9	2	2	2		2	0
July	10	11	12	13	14	‡‡15	16	17	18	19
Reservoir elev.	−305	−323	−341	−359	−373	−407				
Rainfall		0.23	T.	0.50	0.14			0.08		0.39
B. coli. presump.	5	2	2	2		5	5	2	5	9
B. coli. isolation	2	0	0	2		0	2	0	0	5
July	20	21	¶¶22	23	24	25	26	27	28	29
Reservoir elev.										
Rainfall					0.66	0.91				
B. coli. presump.	12		5	2	5	231	2454+	231		12
B. coli. isolation	12		2	0	2	231	2454+	231		12
August	*J.* 30	*J.* 31	1	2	3	4	5	§§6	7	¶¶8
Reservoir elev.		−468								
Rainfall	0.38	T.				T.	0.80		0.04	0.06
B. coli. presump.	5	5	5	5	5		5	2454+	2454+	231
B. coli. isolation	5	2	5	2	2		2	2454+	2454+	231

†† Alum dosage started at Smithsburg.
‡‡ June 12–27 and July 15–20; Antietam Creek partly used.
§§ June 28– July 13 and August 6–7; all mountain supply.
¶¶ Antietam Creek entirely used, July 22–August 5, and practically so August 8–30.

TABLE 1—*Concluded*

August..............	9	10	11	12	13	14	15	16	17	18
Rainfall...........	0.18	0.05		0.50	0.12	T.	0.07		T.	0.02
B. coli. presump....	231	2454+		2454+	231	231	231	12	9	
B. coli. isolation....	231	2454+		2454+	231	231	231	12	5	
August..............	19	20	21	22	23	24	25	26	27	28
Rainfall...........							1.49	T.	0.05	0.15
B. coli. presump....	9	5	2	2	5	5		2454+	2454+	231
B. coli. isolation....	5	2	0	0	0	2		2454+	2454+	231
September............	*A.* 29	*A.* 30	*A.* 31	1	2	3	4	5	6	7
Rainfall...........	0.07	0.23	0.67			T.		0.76	0.35	
B. coli. presump....	5	2	5		2454+	231	12	8	231	12
B. coli. isolation....	2	0	2		2454+	231	5	5	231	9
September............	8	9	10	11	12	13	14	15	16	17
Rainfall...........	0.14			0.10	T.	0.05			0.01	0.03
B. coli. presump....		20	9	5	2	2	2		3	2
B. coli. isolation....		9	5	2	0	0	0		2	0
September............	18	19	20	21	22	23	24	25	26	27
Rainfall...........	0.64		0.95	0.13					T.	
B. coli. presump....	3	2	231	231		12	2	2	0	5
B. coli. isolation....	2	2	231	231		9	2	0	0	0
September............	28	29	30							
Rainfall...........										
B. coli. presump....	2		5							
B. coli. isolation....	0		2							

these numbers from the qualitative results furnished by the data has been carried out by the McCrady method. The description of this method is irrelevant to the present discussion and, therefore, is omitted. For purposes of brevity and clearness the data to be discussed below will be analyzed by monthly periods. The procedure to be followed will consist simply of comparing the data from month to month with corresponding environmental features of the water supply and of pointing out such apparent failures in performance as will appear.

DISCUSSION OF DAILY RESULTS

February. The daily quality of the tap water during February is of considerable interest on account of the sharp rise in B. coli content in the period from the 13th to the 20th, inclusive. A gradual subsidence in the content then occurred, with little or no further fluctuation in quality throughout the rest of the month. The cause of the sharp rise in bacterial content is not hard to determine when

we examine the operating records. The sudden deterioration of the tap water in this case, as in others later to be discussed, apparently is not the result of a decreased amount of applied disinfectant, but rather of the failure of the operator to meet the unusual situation created by dangerous meterological conditions.

On February 13, a change was made from the Antietam Creek to the mountain supply, on account of the increasing amount of water in the Edgemont Reservoir. Shortly before this change a condition of thawing set in on the watershed of the Raven Rock and Warner Hollow streams, resulting in an unusually heavy runoff, as shown by the fact that the Edgemont Reservoir gained in water, between February 12 and 18, to the extent of an approximate depth of 27 feet. During this entire period Raven Rock stream was furnishing its quota of accumulated sediment, since this stream was not eliminated until February 20. It comes about, therefore, that the unusual and excessive B. coli content in the tap water from February 13 to 20 was the direct result of the failure of liquid chlorine disinfection to meet adequately the heavy load placed upon it by the character of the raw water. This breakdown in effective chlorination is not at all surprising when it is borne in mind that the waters reaching the chlorine plant during this period of stress were heavily charged with the cumulative sediments of several months of concentrated frozen pollution, ready to be discharged into the supply on the day of an auspicious thawing temperature. The abnormalities of February tap water are so obvious in their causation that further discussion of their origin is unnecessary.

March. March shows a quality of tap water consistently good and superior in daily content to practically any other month under discussion. This condition is particularly striking in view of the fact that March was an unusually warm month and was subject in addition to heavy rainfalls, as of March 9, 13, and 14. Here daily records of a different nature disclose the cause of good results. A study of the record of water elevations in the Edgemont Reservoir, table 1, indicates the interesting fact that during practically the entire month of March the reservoir contained sufficient water to overflow the spillway and *was not drawing water at all from Raven Rock stream.*

Knowing the apparent advantage in the elimination of Raven Rock and the effect obtained in "equalization, sedimentation, and devitalization" with an overflowing reservoir, it is not at all difficult

to understand the decided superiority of the March water over that of February. The March results typify the advantages of dilution of possible entering concentrations of contamination, and the stabilizing effects of large storage capacity. In this month chlorine was effective because it was acting apparently upon a consistently fair water, in which intermittent and sudden increases in contamination and turbidity were avoided by the happy existence of a stabilizing influence, a full Edgemont Reservoir.

April. The good effect of the above condition is further illustrated in the month of April, when from April 9 to 30 inclusive the reservoir at Edgemont was overflowing. The unusual advantage of the combination of circumstances which supplies an overflowing reservoir and permits of the elimination of the Raven Rock water is well brought out by a comparison of the results preceding and those following April 9. The average daily B. coli content (isolation) of the first nine days of April was 1.8 per 100 cc. as compared with a value for the remainder of the month of only 1.0. This is particularly striking in view of the fact that the rainfall in the second period (April 9–30) was far greater than in the first, to wit: 5.7 against 0.04 inches. It is important to note, however, in this connection that in the first period (April 1–9) the Edgemont Reservoir was *not* full and that Raven Rock stream was in use, neither of which conditions existed after April 9. The April environmental and meteorological conditions give excellent evidence as to the desirability of having some natural or artificial medium available to remove the effect of peak loads now placed on most chlorine plants which treat surface streams of markedly fluctuating qualities, without any preliminary auxiliary treatments for levelling uneven and excessive bacterial contents and turbidities.

It is well to point out also that the results for March and April indicate very clearly the advantages which would accrue to the water supply if the Raven Rock intake were reestablished in the Edgemont Reservoir in such a position as to make its effect less predominant.

May. The month of May differs from the preceding two months in two important and correlated aspects: The quality of the tap waters is decidedly inferior to that of March and April and Raven Rock stream was used during the entire month. These two conditions have much in common, provided rainfalls occur at the same time. During the major portion of the month of May the Edge-

mont Reservoir was full, but the use of the Raven Rock stream with a relatively rapid rate of runoff reduced its beneficial effects after each rainfall. A comparison of the rainfall data with the quality of the tap waters indicates that the *Edgemont Reservoir, though full, is not nearly as efficient a stabilizer of raw waters when Raven Rock is used as when it is omitted.* A comparison of the tap water results in March, April and May shows beyond doubt that the use of Raven Rock water, with any rainfall whatever, causes a deterioration in quality of the water, whereas the omission of the same, even with excessive rains, results in a marked improvement. The following comparison will serve to make this situation clearer:

MONTH	MEAN B. COLI PER 100 CC. IN TAP WATER	RAINFALL (CHEWSVILLE) TOTAL INCHES	RAVEN ROCK
March	1.0	2.41	Not used
April	1.8 (April 1–9)	0.04	Used
April	1.0 (April 9–30)	5.7	Not used
May	3.4	2.93	Used

June. The data obtained during the month of June are not characterized by any unusual conditions. The results in general are consistently fair, due possibly to several causes. The tap water quality is generally good because June was a month of extremely low rainfall (a total for the month of 1.89 inches at Chewsville). The absence of atmospheric disturbances of unusual proportions, the beginning of alum dosage at Smithsburg, and the partial use of Antietam Creek water with relatively good conditions, all resulted in making June a "favorable quality" month.

July. July was unfortunate in its results in a number of ways. In the first place, July 1, 2, and 3 appear with abnormally high B. coli contents, due probably to the single important rainfall in the preceding month, namely 0.65 inch on June 30. With the water 15 feet below the spillway in Edgemont and with Raven Rock in use, the effect of this rainfall was not long in making its appearance.

A gradual improvement in the quality of the water followed July 3, with only intermittent and slight amounts of rainfall, whose effects were largely problematical. On June 15 the partial use, and on July 22, the complete use of the Antietam Creek supply was initiated. This period marks an important epoch in the history of the quality of the Hagerstown supply for the first six months covered

by this study. On July 19 only a slight rainfall (0.39 inch) caused a secondary maximum B. coli content on July 20.

The period of July 24 to 31 is a most interesting one, since it indicates certain conclusions relative to changes in those features of the Hagerstown supply which need most attention. The poor results of this period have no other cause than the complete failure of the filtration plant to perform its function. On July 24 and 25 Diffendal stream was turned into Smithsburg Reservoir, but was not allowed to enter the town. The inferior quality of the tap water of July 25, 26, 27, 29, and 30 is completely due, therefore, to the Antietam Creek supply. The cause is not far to seek. On July 24 and 25 a total of approximately 1.6 inches of rain fell in the vicinity of Hagerstown. The raw water of Antietam Creek became a veritable mud, turbidities of 2000 and 1500 parts per million being reported. To meet this unexpected and dangerous condition a dosage of alum of about 0.6 grain per gallon was used, hardly enough even to begin the coagulation, much less to cause any sedimentation. The final disinfection of a water such as the above with a dose of chlorine of 0.6 parts per million had little effect.

August. In the month of August the mistakes of July were repeated with even worse results. The first few days of August were fair. On August 6 and 7 Antietam Creek gave way to the mountain supply. The reason for the change the records at this writing do not disclose. The change was unfortunate. Given, as initial conditions, practically no water in Edgemont, Raven Rock in use, and a rainfall of 0.8 inch the preceding day (August 5), the final outcome was unavoidable, a B. coli content of over 2400 per 100 cc.

On August 8 use of the Antietam Creek supply was resumed and was continued for practically the rest of the month. The bacterial results from August 8 to 31 require but little comment. Here again, history repeated itself. The same cycle of heavy rainfall, excessive turbidity, low and useless alum dosage, followed by disappointingly unsafe tap waters, was traversed twice again during this same month.

September. The quality of the tap waters in September requires little discussion. The correlations shown in this month are largely the same as those pointed out in the previous discussion and the conclusions indicated verify those already reached.

Some reference should be made at this point to the objection frequently raised by the superintendent against the use, at the filter plant, of increased amounts of alum with excessive raw water tur-

bidities. The objection resulted from the belief that such increases in alum dosage would shorten the effective length of operation of the filter units, on account of the supposedly added accumulations of flocculent material on the surface of the beds, with a consequent lessening of plant capacity. Fortunately the objection is contrary to the findings in other plants and to the theory of coagulation. It is true, of course, that the length of run of a filter bed decreases with increases in raw-water turbidities, when the application of alum is properly made. It is *not* true, that with the *same* raw-water turbidity (however excessive), a shorter run will result with a high alum dose than with a low. Exactly the converse happens and is to be expected, since the addition of sufficient alum to a water of high turbidity will cause increased sedimentation in the basins, less flocculent material to pass to the filters, and increased length of filter run. With insufficient alum and high turbidity, decreased settling occurs in the basins, more sediment passes to filters, and the length of filter run is shortened. It is apparent, therefore, that the objections raised to increased dosage of alum are not valid and have resulted actually in inefficient runs.

CONCLUSIONS

The present inquiry into the nature and causes of the variations in the daily quality of the Hagerstown water supply during the first eight months of 1918 has disclosed several interesting phenomena. They are briefly as follows:

Mountain supply. The factors operating to produce excessive bacterial counts in the tap water when the mountain supply is in use are relatively few. In each of these factors the fundamental cause is excessive rainfall. If one could eliminate the excessive rainfalls the Hagerstown supply would be, with the safeguard of disinfection, hygienically safe. Since this condition is unattainable, it is necessary to remove the effects of excessive run-offs. There are apparently several ways of eliminating these effects. These methods have been used unconsciously in the past and their advantages have been demonstrated. The use of a full storage reservoir and the elimination of Raven Rock stream, if entrance of its water is to remain at the present location, or the use of both Warner Hollow and Raven Rock streams with a new point of entrance at the head of Edgemont Reservoir for water from the latter, appear to be most

desirable. In the absence of such initial conditions as noted, the deleterious effects of heavy rainfalls cannot be equalized successfully and hence peak loads are shifted upon the chlorination, with dangerous results.

If the maximum stabilizing and levelling influences of a natural agency, the Edgemont Reservoir, are not at all times available, it is desirable and necessary that the influence of an artificial agency be added. Such an agency exists in the action of coagulation and sedimentation. The findings of this study show beyond reasonable doubt that, in a number of instances, alum *must* be used on the mountain supply, or else the quality of the water suffers immeasurably.

Antietam Creek supply. On the Antietam Creek supply the only sentry between the effects of heavy rainfall and chlorination is the Bridgeport filtration plant. In the mountain supply, it sometimes happens that reservoir conditions are such as to mitigate the results of excessive rainfalls, but on the Creek supply we have unfortunately no such intermittent assistance. The operation of the Bridgeport plant is characterized by a fatalistic recurrence of objectionable tap water with every unusual intensity of rainfall.

The obvious remedy lies in improved operation of the filtration plant. An immediate change must be made, of course, in the present application of alum, with a later modification undoubtedly in the basins used for coagulation and sedimentation.

In the preceding study no attempt has been made to draw fine distinctions between the daily results or to differentiate so-called good from bad waters. The study has been concentrated upon the relative, rather than the absolute, significance of the B. coli count. Interest has been centered upon the endeavor to determine the causes of the wide variations in a single index, the B. coli, and their future removal. Whether the fecal or the soil type of B. coli has persisted in the tap water is of relatively little significance at this time, when we have learned that the factors which produce marked fluctuations in quality in the Hagerstown supply are of such character as to demand their immediate eradication. The purpose of the study has been to determine the deviations from the normal, and not the significance of the absolute, B. coli contents.